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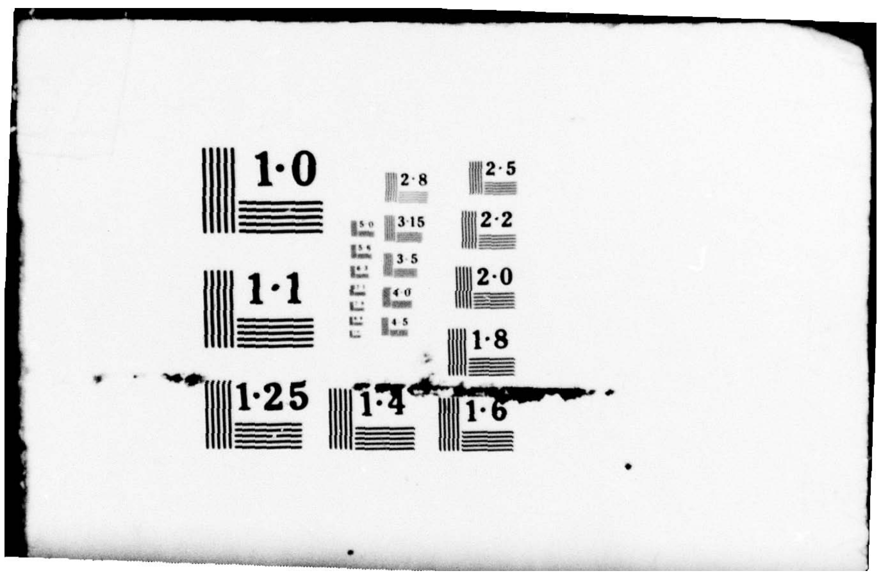
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ACOUSTIC EMISSION METHOD FOR STRESS AND STRAIN DETERMINATION

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Acoustic Emission (AE) was detected during magnetization of a nickel and was also found to depend on applied stress. Varying AE outputs were observed on several ferromagnetic materials under alternating magnetic field. This magnetomechanical AE phenomenon has a potential of performing nondestructive measurements of residual stresses in structures, components and weldments, and we examined systematically effects of applied stress and magnetic field strength in ferritic steels. Several carbon steels, A533B steel and Armco iron were tested in annealed or normalized condition. By employing two AE transducers (AC 175L and MAC 500), rms voltages were measured at two frequency ranges. Maximum stress level was 350 MPa. It was found that 1020 steel shows the highest AE response among the materials tested. Residual stress levels can be determined by monitoring the outputs of two AE transducers for a given material condition. The amount of prior cold work can also be obtained by monitoring this AE phenomenon. Details of experimental findings will be discussed towards the goal of developing a new method of nondestructive evaluation of residual stress and material conditions.

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ACOUSTIC EMISSION METHOD FOR STRESS AND STRAIN DETERMINATION

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Introduction

Significant effects of stress, plastic deformation and microstructures on the magnetic properties of ferromagnetic materials have been well known and documented.(1,2) In measuring the elastic strain and residual stress, magnetostriction has been utilized widely.(3,4) When the level of applied field is varied, the shift in magnetic domain structures produces ultrasonic waves(5), of which intensity varies with stress.(6) Such ultrasonic waves are generally called acoustic emission (AE), and in the instances arising from magnetostriction, we will refer to them as "magnetomechanical AE". This effect is mechanical analogue of "Barkhausen effect".(7) The intensity of induced electrical pulses due to domain boundary movement has been correlated to applied stress level.(3,4,8) In the absence of magnetic field, AE due to domain wall motion was also observed during tensile testing.(9)

Since the magnetomechanical AE is a potential nondestructive testing method for residual stress determination, we conducted a series of experiments determining the level of AE signals as a function of the composition, applied magnetic field and external stress as well as plastic strain. Results are reported here together with preliminary interpretation of their possible origins of the observed behavior.

Experimental Procedures

A series of iron and steels was used in this study. A commercially pure iron (magnet iron) and AISI 1020 steel were fully annealed at 1183 K for 1 hr. in an inert atmosphere and furnace cooled. AISI 1045 and 1065 steels were normalized by heating to 1123 K for 30 min and air-cooled (albeit in an inert atmosphere). A low alloy steel, ASTM A 533 B, class 2, was tested in the as-received condition having tempered bainite plus ferrite microstructure.

Round tensile specimens of the half-size ASTM standard geometry (E-8) were machined. The gauge section has 6.3 mm diameter and 32 mm length and the total length was 84 mm. The threaded grip sections were 12.7 mm diameter (16 mm for magnet iron and 1020 steel). Following heat treatment and thorough cleaning, a sample was mounted in threaded grips with teflon tape lubrication. The experimental set-up is shown in Fig. 1. Two transducers for AE detection were attached to the flat ends. These were a resonant transducer with the nominal center frequency of 175 kHz (AC 175L, Acoustic Emission Technology Corp. (AETC), Sacramento, CA) and a miniature sensor with the nominal resonant frequency of 500 kHz (MAC-500, AETC). The former was coupled via viscous resin, while the latter was glued to the sample using cyanoacrylate ester. The transducer outputs were amplified 60 dB using preamplifiers (160, AETC) with bandpass filter plug-ins of 125 to 250 kHz and 125 to 1000 kHz, respectively. The rms voltages of the amplified outputs were measured using true rms reading

voltmeters(3400 A, Hewlett-Packard, Palo Alto, CA)and X-Y-Y′ recorder.

Stressing and plastic deformation of a sample was performed using a floor-model Instron. The magnetic field on the sample was generated by a solenoid encircling the gauge section of the sample. It was powered through a variac with AC voltages of up to 140 V at 60 Hz. The maximum magnetic field generated was 2550 A/m rms at the center of the solenoid, which had the casing of 25 mm inside diameter and of 33 mm length. The sample was magnetized longitudinally and the magnetic circuit was open-ended.

Result and Discussion

In this study we first examined AE responses due to magnetization of different sample in order to see the effect of permeability and saturation magnetization. We also studied the effect of external stress on magnetomechanical AE. A special attention was given to the sense of the applied stress with respect to the magnetostriction of samples.

1. Effect of magnetic field

Typical results of AE output (referred to at the preamplifier input) vs. the field strength are shown in Fig. 2. Here, applied stress was absent and the results of the low frequency transducer (AC175L) were plotted. Similar to a typical magnetization curve, AE responses due to increase in the field strength can be divided into four regions; Region 1 is an initial increase of AE response; Region 2 has the linear behavior, Region 3 shows increasingly greater deviation from the linearity; and Region 4 tends to reach a saturation level.

Compositional effects on AE behavior found in Fig. 2 are summarized as: (1) with increasing carbon content, the start of Region 2 shifts to a higher magnetic field level; 2) the maximum slope in Region 2 shows a maximum at 0.2% carbon; 3) the field strength at the start of Region 3 is higher for a steel with higher carbon content; and 4) the intensity of AE at a saturation is highest for 0.2% carbon composition. It is known that the permeability and saturation magnetization decrease with increasing carbon content in iron [1,2,10]. Thus, magnetomechanical AE is not solely determined by such magnetic properties of the sample.

2. Effect of external stress

An example of variation in the AE intensity-field strength curves due to stres is shown in Fig. 3. Results for A 533 B steel are given for each of the two transducers at three levels of stress, 0, 172 and 344 MPa. Significant drop in the maximum AE intensity was observed by applying external stress, which also affected the shape of the AE intensity vs. field strength curve. For this material, the AE intensity decreased repidly with stress of approximately 100 MPa, and further decreases were limited.

The compositional effects of these results are summarized in Fig. 4, where the AE intensities at three stress levels are plotted against the nominal carbon content. A maximum was observed at the carbon content of 0.2%. The result

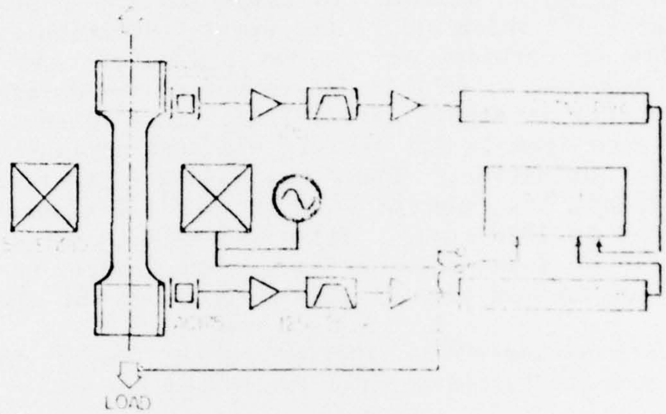

Fig. 1 Schematic experimental set-up.

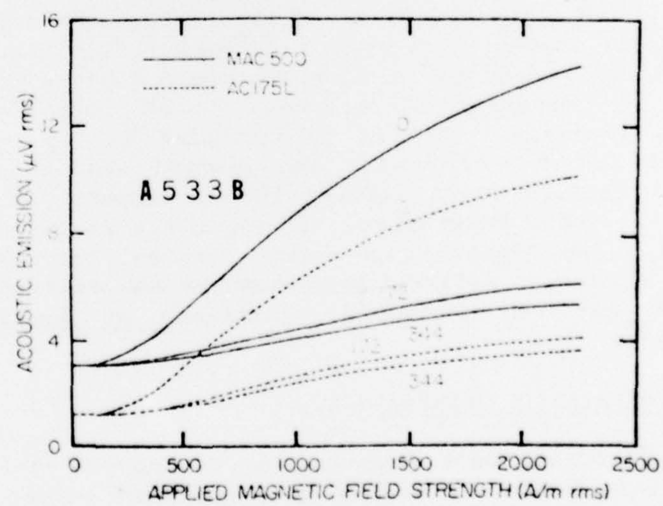

Fig. 2 Acoustic emission vs. applied magnetic field strength for five materials at 175 kHz without applied stress.

indicates that the AE output is not solely controlled by the ferrite content. Magnetomechanical AE is believed to originate from a sudden motion of magnetic domain boundary[5,6] which shifts the spatial distribution of magnetostriction. The dispersion of carbides in the ferrite matrix and mixing of ferrite and pearlite are expected to inhibit and to retard the domain boundary motion. The lower AE intensity at higher carbon levels is a direct result of this effect. Commerically pure iron is all ferrite and such an inhibition effect is limited to nonmetallic inclusions. Thus, the domain boundaries are expected to have less restrictions. Yet, the AE intensity in the observed frequency range was lower than that in 1020 steel. Differences in the size of magnetic domains or in the mobility of domain boundaries were apparently responsible for the above observation, but further studies will be required for clarification.

When a uniaxial stress σ^A is applied to the sample which is magnetized by a field H, the magnetoelastic interaction energy can be written as[10]

$$E_I = -1.5\lambda \cdot \sigma^A \cdot \cos^2\psi$$

where λ is the magnetostriction and ψ is an angle between the magnetization direction of a domain and the stress axis.

When λ is positive, as in most iron and steel[10], the domain, which has $\psi = 0$, becomes most stable under a tensile stress ($\sigma^A < 0$) because of the largest negative E_I. In this study, H was parallel to the axis of the sample, so most of the domains should have $\psi = 0$ at a high field strength. On the other hand, a compressional stress ($\sigma^A < 0$) makes these domains most unstable. Therefore, we expect to observed differences of AE responses between tensile and compressive loading. This is demonstrated in Fig. 5, where the results of A533B steel (at H = 750 A/m) are plotted against the applied stress. As expected, a tensile sress lowered the AE outputs due to the stabilization of the domains. Under compressive stresses, the AE output first increased due to positive E_I. At higher compressive stresses, however, the observed AE level started to decrease, reflecting presumably the refined domain structures under stress[3,8] and the increased resistance of domain wall motion due to stresses[1,2].

3. Effect of plastic deformation

Stress and field strength dependencies of magnetomechanical AE vary with prior plastic strain. The AE intensity vs. stress curves for A533B steel sample deformed 15% are shown in Fig. 6. The corresponding curves before the deformation were given in Fig. 5. Significant changes are evident. (1) At zero stress, the AE intensity after plastic deformation decreased at 500 kHz, but increased at 175 kHz. (2) After deformation, the stress dependency became more symmetrical with respect to the sense of the applied stress. It is certain that the variation in magnetostriction and the development of internal stress due to plastic deformation[10] are responsible for these observations. It is not feasible to separate these contributions at present, but independent measurements of magnetostriction are planned. This technique may prove to be a useful tool in determining internal stresses due to dislocation substructures. It is expected that more extensive work will enable one to measure the level of

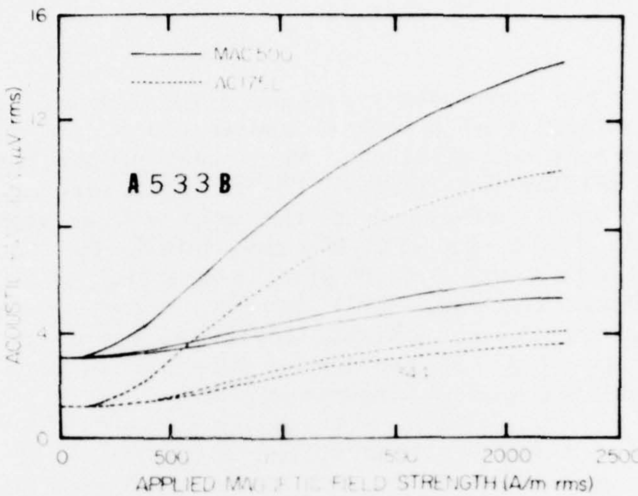

Fig. 3 Acoustic emission vs. applied magnetic field strength for A533B steel at three stress levels, 0, 172 and 344 MPa. Solid lines for 500 kHz and dotted lines for 175 kHz.

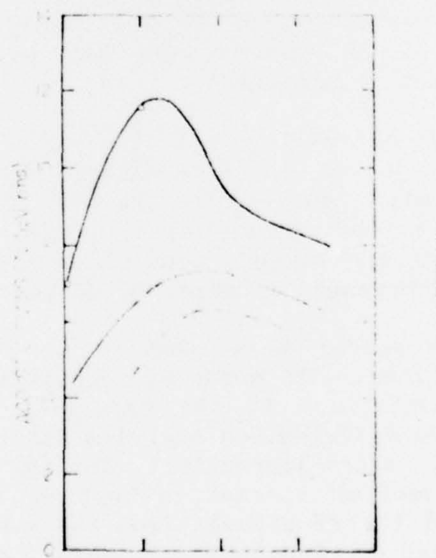

Fig. 4 Acoustic emission at three levels (0, 69 and 138 MPa) vs. carbon content of iron and plain carbon steels.

plastic deformation of ferromagnetic materials.

Application

On the basis of the above observations, several experiments were performed to explore the feasibility of practical applications. In one series, a steel weld under tensile stress was examined. Mild steel plates, 9.5 mm thick, were joined by manual arc welding and strips, 25 mm wide, were machined. Two solenoids were placed on both surfaces over the weld and energized by 60 Hz AC. The surface magnetic field was 1130 A/m rms, normal to the surface of the welded strip. The AE output was 3.2 μV after correction of background noise, using a resonant transducer (AC 750, AETC) coupled to the surface about 50 mm from the weld. The appplication of nominal tensile stress of up to 30 MPa reduced the output at a rate of 0.23% per MPa. This stress sensitivity appears to be adequate for residual stress determination.

Another series of tests utilized 1045 steel bolts, heat-treated to the tensile strength level of 690 MPa. The bolts were 12.7 mm diameter and 127 mm long. Using an encircling solenoid with 2250 A/m rms field strength at 60 Hz, the AE level was 7.3 μV with background correction. An AE transducer (AC 750) was coupled to one end of the bolt. Stress sensitivity was 0.29% per MPa under tensile loading. Again, this appears to be sufficient for practical use.

These results demonstrate that practical devices can be produced to measure the stress level in ferromagnetic structural components. Determination of prior cold working and fatigue is also possible. Another potentially useful application is the evaluation of heat treatment. It is expected that the frequency spectrum of AE signals can aid in the the differentiation of different heat treatment conditions.

When magnetically soft materials, such as silicon iron sheet and amorphous iron alloy foil, were subjected to alternating magnetic field, very strong AE singals were produced. The monitoring of their magnetic properties via magnetomechanical AE method appears to be promising. This method also can be utilized in monitoring the texture control of some of ferromagnetic materials, since the domain wall movement is expected to be anisotropic.

These observations reported here need to be expanded further in order to develop practical devices. The means of magnetization, the use of differential methods to cancel variations in the materials response and the use of AE counting and amplitude distribution analyses should be explored. The use of an encircling solenoid is often impractical, but the use of a yoke (as in magnetic particle testing) required special precaution to ensure reproducible field strength and to avoid the AE signals from the yoke itself. The orientation of magnetic field is also an important parameter, especially in relation to the detection of biaxial stress fields.

Conclusions

Magnetomechanical acoustic emission phenomenon was evaluated of its potential of nondestructive determination of residual stress and prior plastic strain of ferromagnetic materials. Its intensity and frequency spectrum were found to

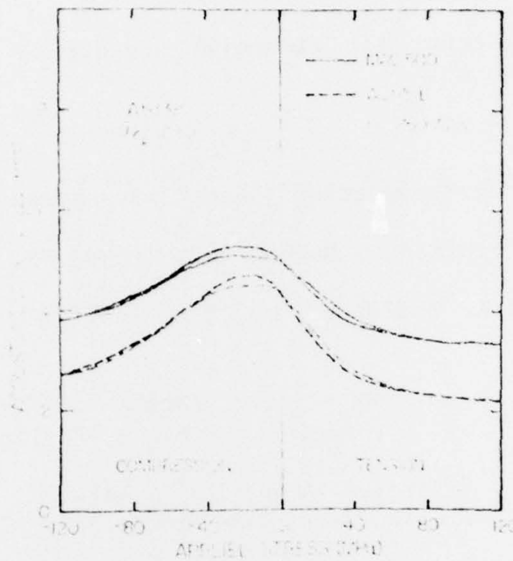

Fig. 5 Acoustic emission vs. applied stress for undeformed A533B steel at the magnetization level of 750 A/m.

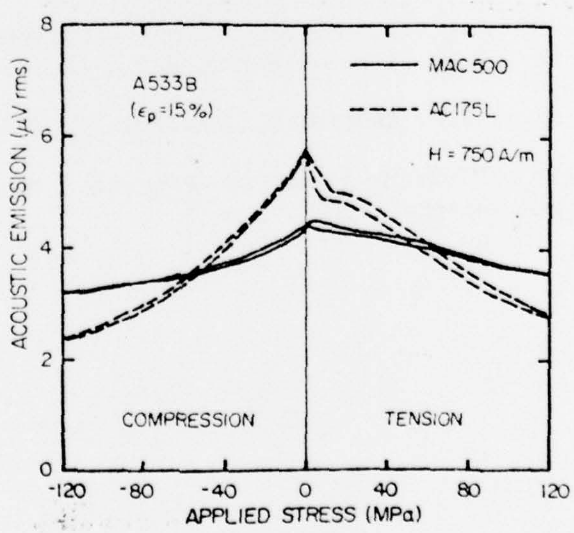

Fig. 6 Acoustic emission vs. applied stress for A533B Steel deformed 15%.

vary sufficiently with these parameters, providing the basis for practical applications. Much effort is needed to develop useful devices and to clarify various sources that contribute to this AE phenomenon.

Acknowledgement

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